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Fatigue design factors for ECAPed materials

F. Djavanroodi*, M. Ebrahimi, B. Rajabifar, S. Akramizadeh

Department of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

Equal channel angular pressing (ECAP) was successfully performed on commercial pure aluminum, aluminum 6061 alloy and commercial pure copper by route B_C. Tensile and fatigue (under constant stress) tests shows a significant enhancement in mechanical properties consisting of hardness, yield strength, ultimate tensile strength and endurance limit, but the ductility of the alloys reduced with employing this process. Two fatigue design factors K_l and K_h has been suggested to co-related fatigue data from coarse grained (CG) to ultra-fine grained (UFG) materials.

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1. Introduction

Severe plastic deformation (SPD) is an efficient method for producing ultra-fine grain (UFG) materials [1]. Various SPD techniques like equal channel angular pressing (ECAP) [2,3], cyclic extrusion compression (CEC) [4], high pressure torsion (HPT) [5], accumulative roll bounding (ARB) [6] and repetitive corrugation and straightening (RCS) [7] have been introduced for fabricating nano-structured materials. It is generally considered that nano-structured materials have high mechanical and super-plasticity properties [8]. Among all SPD methods the ECAP process has proved attractive and has been investigated because of no substantial change in the geometry of the sample. As can be seen in Fig. 1, a sample is pressed through a die with two intersecting channels equal in the cross-section with a die channel angle of ϕ and a corner angle of Ψ.

In the ECAP process there are four fundamental routes between each repetitive pressing as is shown in Fig. 2. These are: route A—that the sample is repetitively pressed without any rotation, route B_A—that the sample is rotated by 90° in alternative direction between each pass, route B_C—that the sample is rotated in the same sense by 90° and route C—that the sample is rotated by 180° between each pass [9]. These routes create different slip systems during the pressing operation so that various microstructure and mechanical properties can be achieved [10,11]. By using route B_C, a uniform distribution of the effective strain and a material with isotropic properties can be obtained using the ECAP process. Influences of die parameters and friction coefficient values on the effective strain distribution have been investigated by the authors [12].

Fatigue life of components consists of two stages: Stage one – high-cycle fatigue (HCF) – at relatively small strain amplitudes, the crack initiation stage dominates most of fatigue life. Stage two – low-cycle fatigue (LCF) – which is associated mostly with the crack propagation, which occurs at relatively large strains [13]. It is possible to distinguish quantitatively between the high and low cycle fatigue if the total life fatigue diagram is considered where the number of reversals to failure is plotted versus the total strain amplitude [14–18]. For the UFG materials produced by SPD techniques, a variety of increased or decreased fatigue properties in different researches are reported. However, most UGF materials produced by SPD techniques exhibit similar properties: their high cycle fatigue (HCF) strength is considerably higher than for coarse grain (CG) materials and their low cycle fatigue (LCF) is inferior in its ability to sustain cyclic loading in the LCF region [19]. The factors affecting the fatigue limit are: (a) chemical composition of the alloy, (b) type of dislocation slip, (c) grain size, (d) dislocation density and distribution, (e) texture, (f) residual stresses, (g) stress ratio, (h) mean stress, (i) frequency, (j) temperature, (k) environment, (l) specimen shape and dimensions, (m) surface conditions such as finishing and hardening/softening treatment of the surface layer [19–23]. The fatigue limit of pure f.c.c. metals (Cu and Al) with relatively high stacking fault energy and wavy slip behavior is not affected by the grain size [23]. The striking result of grain

* Corresponding author. Tel.: +9821 77240203.
E-mail address: javanroodi@iust.ac.ir (F. Djavanroodi).

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Table 1
Chemical composition of commercial pure aluminum, Al6061 and commercial pure copper.

Material	Composition						
Al1060	Al, base	Fe, 0.212	Si, 0.100	Cu, 0.015	Zr, 0.013	Ti, 0.009	Mg, 0.007
Al6061	Al, base	Mg, 0.800	Fe, 0.700	Si, 0.400	Zn, 0.250	Cu, 0.150	Ti, 0.150
Cu	Cu, base	P, 0.027	Sn, 0.005	Zn, 0.002			

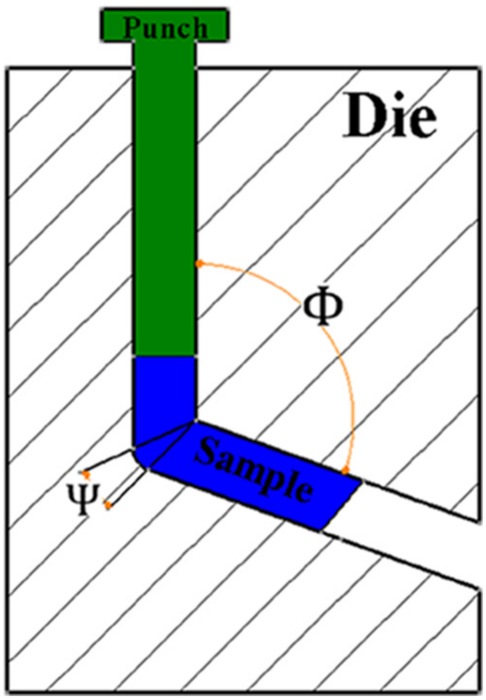

Fig. 1. The schematically diagram of ECAP die.

refinement down to submicrocrystalline scale is that these materials exhibit a prominent rise in their fatigue performance after ECAP.

The determination of endurance limits by fatigue testing is now routine, though a lengthy procedure. For preliminary design and failure analysis, a quick method of estimating endurance limit is needed. Also obtaining an endurance limit modifying factor which can be used to account for ECAPed process effect on the base material is very useful for designer when endurance limit of mechanical element are required. In this study, the ECAP process has been performed on three types of alloys (commercial pure aluminum, Al6061 and pure copper) by route B_C with the die channel angle of 90° and corner angle of 15°. Optical and scanning electron microscopy (SEM) has been used to evaluate and measure grain size of samples before and after pressing. Mechanical properties (hardness and tensile tests) and the *S–N* curve (fatigue strength–number of cycles) of base and the ECAPed materials are compared. Two fatigue design factors obtained from uniaxial test, K_l and $K_{h,}$ have been suggested to co-related fatigue data from coarse grained to ultra-fine grained materials.

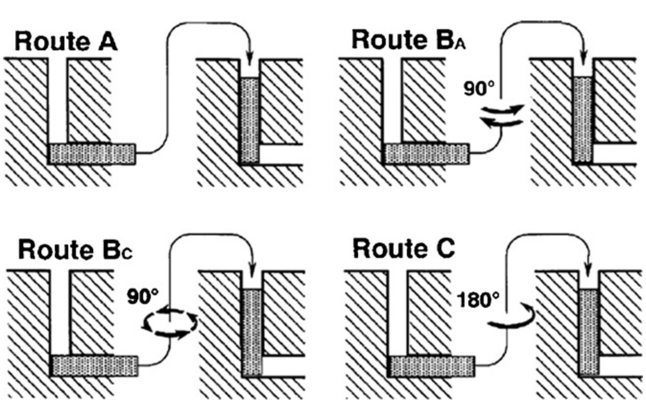

Fig. 2. Four fundamental routes in the ECAP process [9].

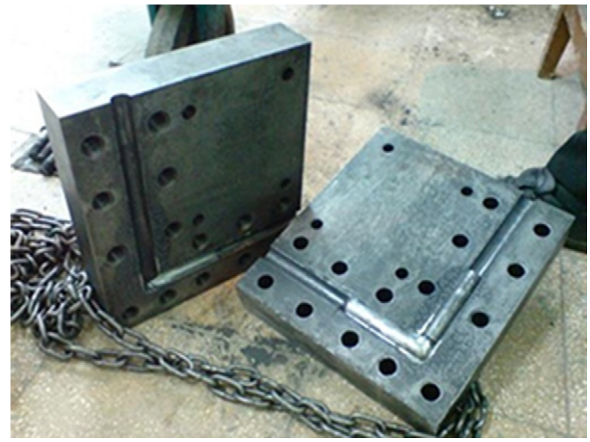

Fig. 3. ECAP die with $\Phi = 90°$ and $\Psi = 15°$ used for this study.

2. Experimental procedures

The ECAP die was designed and manufactured with an internal angle of $\varphi = 90$ between the vertical and horizontal channels and a curvature angle of $\psi = 15$. Fig. 3 shows a general view of the ECAP die. Three types of alloys with the diameter of ~20 mm were used for this study: Al1060, Al6061 and pure Cu. The chemical compositions of these materials are shown in Table 1. The Al6061samples were solid-solutionized at 530 °C for about 2.5 h and then cooled to room temperature by slow cooling in the furnace (furnace cooled, FC). The pure Al samples were annealed at 360 °C for about 20 min and then cooled to room temperature by slow cooling in the furnace. The pure copper samples were also normalized at 500 °C for about 1 h and then cooled to room temperature in air. The purpose of these heat treatments was to increase the workability and ductility of the materials. The initial grain size measured after heat treatment and prior to ECAP was approximately 65, 110 and 120 μm for Al6061, Al1060 and pure Cu, respectively as shown in Table 2. The ECAP process was performed at room temperature with a ram speed of 1 mm s^{-1} and using samples lubricated with MoS_2. Route B_C was used for the ECAP process. Fig. 4 represents the shape of ECAPed samples. Hardness was measured on a plane perpendicular to the extrusion axis of the ECAP-processed materials,

Table 2
The grain size magnitudes for initial and final passes in Al1060, Al6061 and pure copper.

	Initial (mm)	ECAPed (nm)
Al1060	110	710
Al6061	65	590
Pure Cu	120	600

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